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LIGHTWEIGHT GAAS(P) SEMICONDUCTOR INJECTION LASERS.(U)
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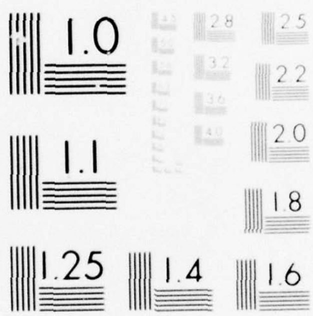
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LIGHTWEIGHT GaAs(P) SEMI CONDUCTOR LASERS

Final Report

G. Craford
W. Groves
R. Herendeen

October 1969

Prepared for:
U.S. ARMY ENGINEER
RESEARCH AND DEVELOPMENT LABORATORIES
FORT BELVOIR, VIRGINIA

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SUMMARY

During the course of work under the contract, two basic GaAsP laser device configurations were fabricated and mounted in two different package types. The device configurations were:

- Rectangular Parallelepiped (Standard)
- Planar

The devices were mounted on:

- Tungsten Post
- BeO Blocks on TO-5 Header

It was demonstrated that the planar device BeO mounted on a TO-5 header was superior to the other combinations. At room temperature, this device gave 5 watts peak power output for a current pulse of 40 amps having a duration of 100 nanoseconds at a repetition rate of 1 KHz. Increasing the repetition rate of this device gave the following power outputs:

- 3.9 watts @ 10 KHz
- 2.7 watts @ 20 KHz
- 1.9 watts @ 40 KHz

Four element and sixteen element arrays were manufactured and delivered based on the planar device geometry. The sixteen element array delivered 55 watts peak power for a current pulse of 40 amps having a duration of 100 nanoseconds at a repetition rate of 4 KHz. The average power of the array under these conditions was 22 milliwatts.

FOREWORD

This report was prepared by Monsanto Company, Electronic Products and Controls Division, Electronic Special Products Business Group under contract with the U.S. Army Research and Development Laboratories, Contract Number DAAK02-69-C-0180.

Performance under the above contract was administered by Mr. S. E. Smathers on behalf of the U.S. Department of the Army, Night Vision Laboratories, Ft. Belvoir, Va.

This report covers work performed during the period of December 12, 1968 thru June 12, 1969.

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I. INTRODUCTION

The purpose of this program was to develop single element and multi-element GaAsP laser devices having a spectral output of $8575 \, {}^{+150}_{-\ 50}$ Å. Single element units were to be mounted in a TO-47 header and the 16 element array emitting area was to be within the confines of a TO-5 header. In order to meet the specification requirements, the following factors were investigated:

- Material Composition Control
- Dopant Control
- Thermal Optimization
- Device Configuration

II. MATERIAL PREPARATION

$GaAs_{1-x}P_x$ wafers, doped n-type, about 200μm thick and 2-3 cm^2 cross section area were grown by vapor epitaxial deposition on GaAs substrates in a laboratory reactor previously described[(1)]. This system employs the hydrides, arsine and phosphine, with elemental gallium and hydrogen chloride as reagents and purified hydrogen gas as the carrier. To minimize strain and dislocations introduced by lattice mismatch, an interlayer with a compositional gradient of about 0.2 mole % of GaP micron was grown between the alloy layer and GaAs substrate.

The composition of the alloy layers was controlled by adjusting the flow of phosphine and arsine into the reactor. A non-destructive X-ray diffraction technique[(2)], accurate to ± 1%, was used to measure the surface composition of the completed

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(1) "Manufacturing Methods for Epitaxially Growing Gallium Arsenide - Gallium Phosphide Single Crystal Alloys". Technical Report AFML-TR-68-319, p. 179.

(2) Ibid., p. 142

layers. After several calibration runs the reproducibility of a given composition, as determined by both X-ray measurement and emission wavelength, was within $\pm$ 1% as shown in Figure 1.

Typically, to produce a 6 mole % GaP alloy 1% PH_3 in H_2 at cm^3/minute and 10% AsH_3 in H_2 at 36 cm^3/minute, corresponding to a vapor composition of 2.4% phosphorus, was fed into the reactor. This solid to vapor composition ratio is in agreement with previous results obtained with a different system[3].

A very slight dependence of alloy composition on substrate position in the furnace was observed. The extreme variation over a distance of two inches in a temperature gradient of 25°C/in was a decrease of less than 1 mole %.

Doping control in the n-type $GaAs_{1-x}P_x$ layers was accomplished by bleeding a dilute (about 1000 ppm) mixture of diethyl telluride in H_2 into the reactant gas stream at a controlled rate. Electrical measurements were made by conventional techniques on samples taken from each end of each wafer. Following the X-ray measurement, small crosses were cut ultrasonically after which the GaAs substrate and graded interlayer were lapped off. Indium dots alloyed to the arms of the crosses provided electrical contacts to the 1 mm^2 active area of the van der Pauw samples. Mobility and free carrier concentration were calculated from the Hall constant and resistivity results.

Following preliminary calibration runs dopant concentration, as determined by the electrical measurement, was reproducible within less than a factor of two. A definite dependence of doping level on substrate position in the furnace was observed. Typical values

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(3) "Manufacturing Methods for Epitaxially Growing Gallium Arsenide - Gallium Phosphide Single Crystal Alloys". Technical Report AFML-TR-68-319, p. 116

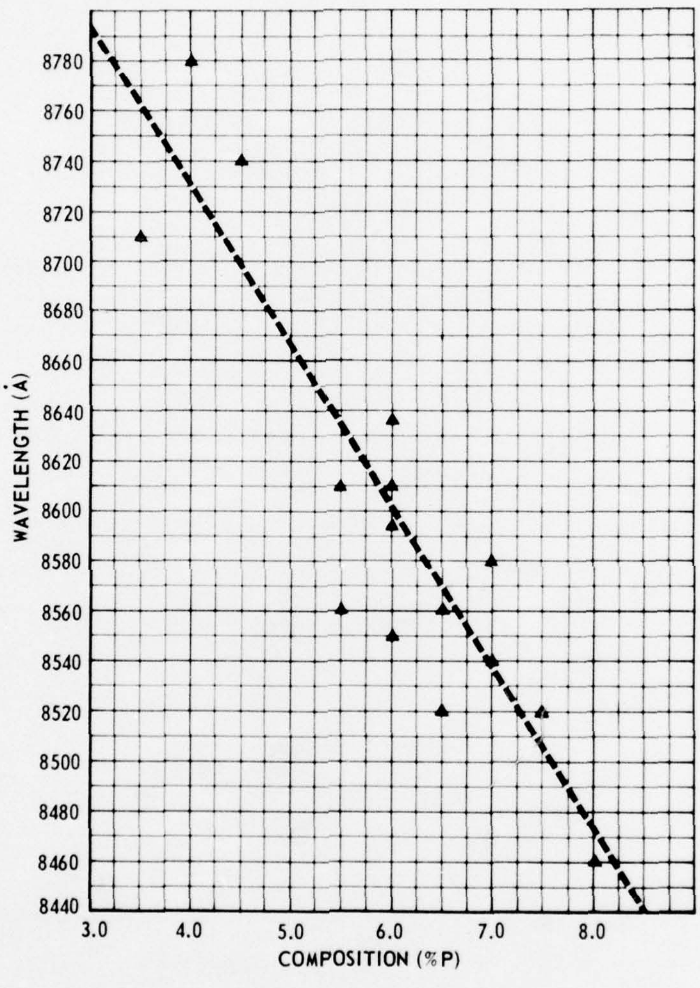


Figure 1. Emission Wavelength vs Phosphor Composition for Vapor Grown Epitaxial GaP Layer.

were 4 x 10^{18} cm^{-3} at the front of the first wafer and 2 x 10^{18} cm^{-3} at the back of the second.

III. MATERIAL EVALUATION

The evaluation of the material consisted of fabricating twenty devices from each wafer and investigating various aspects of device performance. By this means, it was possible not only to select satisfactory wafers for devices, but also to optimize growth conditions and thus, obtain a high yield of satisfactory wafers.

A total of twenty-four wafers were grown and evaluated in connection with this contract. Table I lists the wafers studied with the corresponding mole % GaP, carrier concentration (n), peak emission wavelength (m), differential quantum efficiency from one end of the chip (η_{ext}), threshold current density (J_{th}), and figure of merit ($\eta_{ext}/J_{th}10^{-4}$). The figure of merit gives a better indication of the overall performance of the devices than either η_{ext} or J_{th} alone. All of the performance data listed in Table I represents averages over the 20 diodes fabricated from each wafer.

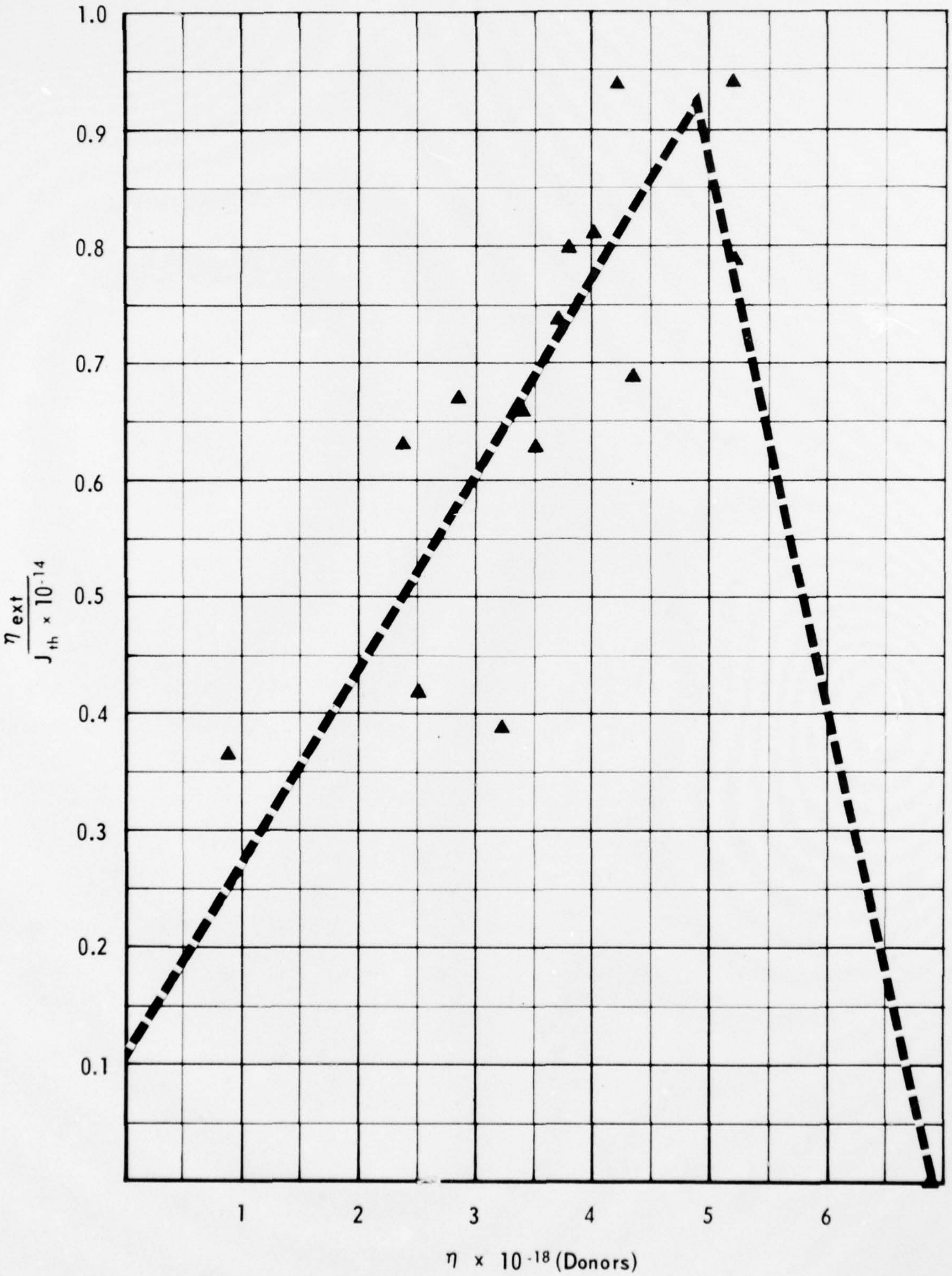
It was found that the performance of the devices increased with carrier concentration up to approximately 6 x 10^{18} atoms/cm^3. At this level it was found, both here and in earlier work, that the performance decreases sharply with increasing carrier concentration. This, it is thought, is due to an increase in structural defects in the crystal related to an excessively high impurity concentration. A plot of figure of merit vs. carrier concentration is shown in Figure 2.

This emission spectra of the devices was studied in order to

TABLE I

Wafer Number	% P	$n \times 10^{18}/cm^3$	m(300°K) Å	η_{ext} %	J_{th} (amps/cm^2)	$\eta_{ext}/J_{th} \times 10^{-4}$
G 20-19-1A	7.5	3.24	8360	5.8	148K	0.39
G 20-20-1A	6.5	6.90			280K	0
G 20-21-1A	7.5	3.50	8520	7.3	116K	0.63
G 20-21-2-1A	6.5	2.20	8520	4.1 - 6.8	104K - 144K	0.28 - 0.65
G 20-22-1A	8.0	0.90	8450	6.2	170K	0.365
G 20-23-1A	7.0	4.00	8540	6.8	84K	0.81
G 20-24-1-1A	7.0	5.20	8580	7.1	90K	0.79
G 20-24-2-1A	6.5	4.20	8560	7.9	84K	0.94
G 20-25-1-1A	4.5	4.34	8740	6.8	98K	0.69
G 20-25-2-1A	3.5	2.37	8710	6.8	108K	0.63
G 20-26-1-1A	4.0	3.80				
G 20-26-2-1A	4.0	3.40	8780	6.6	100K	0.66
G 20-27-1-1A	5.5	2.84	8610	6.2	92K	0.67
G 20-27-2-1A	5.5	2.87				
G 20-28-1-1A	6.0	5.20	8610	7.9	84K	0.94
G 20-28-2-1A	5.5	2.48/ - 4.18	8560	4.3 - 6.4	112K	0.38 - 0.57
G 20-29-1-1A	6.0	3.71	8590	6.8	92K	0.74
G 20-29-2-1A	6.0	3.47				
G 20-30-1-1A	6.0	2.50	8550	5.2	124K	0.42
G 20-30-2-1A		1.23	8566	5.7	112K	0.51
G 20-31-1-1A	6.0	3.10	8590	5.5 - 6.6	84K - 104K	0.53 - 0.79
G 20-31-2-1A		1.89				
G 20-32-1-1A	6.0	3.80	8636	6.4	84K	0.80
G 20-32-2-1A	5.5	2.70				

Figure 2. Figure of Merit vs. Donor Concentration



determine the optimum alloy composition for obtaining the required $8575 \begin{smallmatrix} +150 \\ -50 \end{smallmatrix}$ Å output. A plot of peak emission wavelength vs. alloy composition is shown in Figure 1. It was determined from this that 6 mole % GaP was a suitable target composition. Furthermore, due to the high degree of alloy uniformity across the wafer, the bandwidth of the emission peak was as narrow as that obtained with GaAs, typically < 50 Å full width at half height for normal operating currents of 2 to 3 times threshold.

IV. FABRICATION OF SINGLE ELEMENT LASERS

Two types of single element laser chips were fabricated and evaluated. The first, referred to as a "standard" chip (rectangular parallelepiped), measured 4 mil x 4 mil x 10 mil long is shown diagramatically in Figure 3. The other, referred to as a "planar" chip, measured 4 mil x 15 mil long x 25 mil wide is shown diagramatically in Figure 4. In the "standard" device the PN junction was diffused into the entire wafer and dicing of the device defined the active area (4 mil emitting junction width and 10 mil cavity length). In fabricating the "planar" device diffusion masking techniques were used and the chip size was considerably larger (25 mil face width and 15 mil cavity length) than the standard chip. The active area of this "planar" device was, however, approximately the same as that of the "standard" device.

Fabrication of the "standard" 4 x 4 x 10 mil laser material preparation began with an organic rinse on wafers which were approximately 20 mils thick and 1 inch in diameter. The wafers were placed in a quartz ampule along with the dopant and sealed off under vacuum. The p region was diffused into the n-type GaAsP epitaxial layer in a high temperature diffusion furnace following which the wafers were cleaned. After the organic rinse, a second

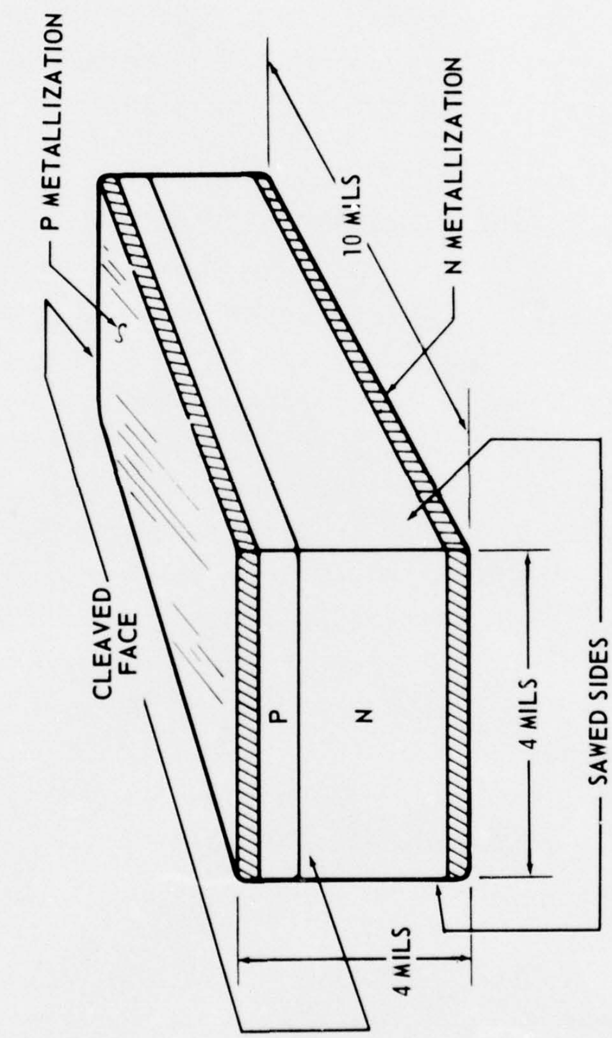


Figure 3. Rectangular Parallepiped Laser Die.

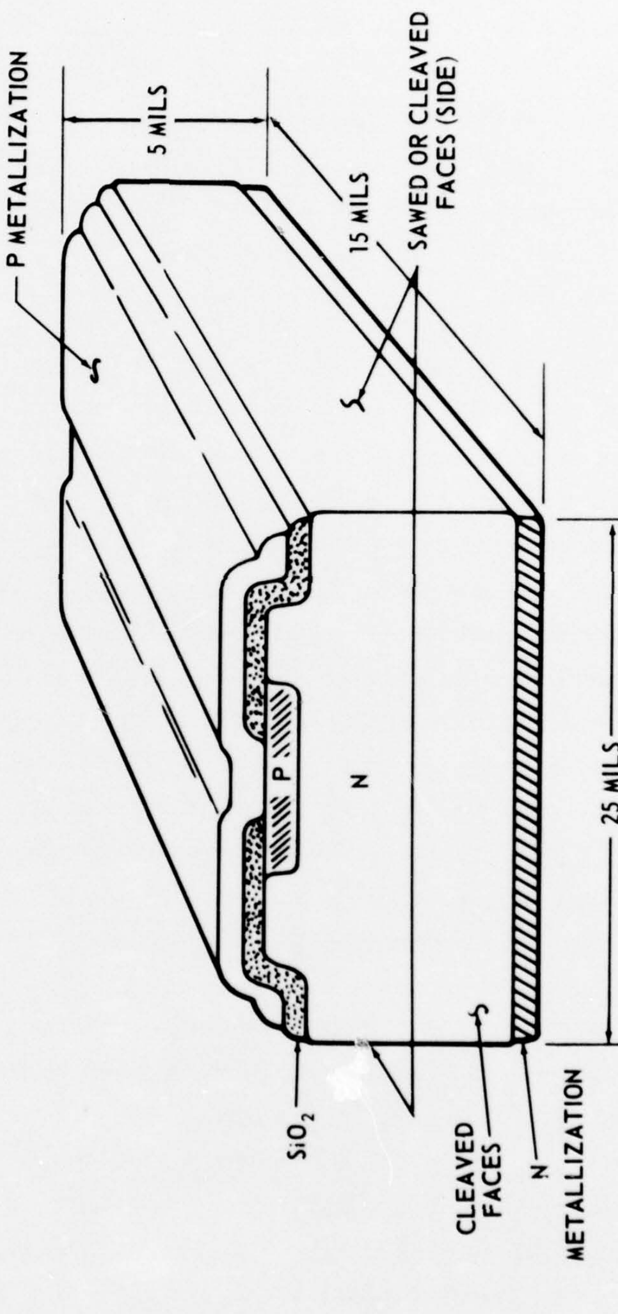


Figure 4. Planar Laser Die.

diffusion was performed to modify the junction profile. The finished wafers were organically rinsed followed by a check on the junction profile. Wafers having a suitable junction profile were metallized on the p side by vacuum deposition. The metallized wafers were back-lapped to desired thickness, followed by an organic rinse. Metallization on the n-side was achieved by vacuum evaporation and plating followed by an additional vacuum evaporation. The metallized wafer was cleaved and sawed and the resulting dies dried in a nitrogen atmosphere.

V. FABRICATION OF THE "PLANAR" SINGLE ELEMENT LASER

Epitaxial wafers about 1 inch in diameter and 20 mils thick were subjected to an organic rinse followed by growth of silicon dioxide and a photoresist process with a suitable mask. After another rinse, junctions were diffused into the epitaxial layer with p-dopant under vacuum at high temperature, followed by rinsing and SiO_2 removal. A second diffusion was performed to achieve the graded junction after cleaning the wafers. In order to improve the cavity cross section, the p-surface was subjected to a chemical etch. The wafer was cleaned in an organic rinse and silicon dioxide deposited. A photo resist process was used to prepare the wafers for a high temperature flash diffusion enabling proper dopant concentration for good ohmic contact, followed by flash diffusion with p-dopant under vacuum. The wafers were cleaned organically and the SiO_2 removed. The wafers were subjected to a photo resist and chemical etch process in order to define mesas between devices centered every 25 mils. Wafers were cleaned and a new deposit of SiO_2, (2400Å) grown in preparation for a photo resist process for metallization. The p-side metallization was accomplished by vacuum evaporation following which the wafer was back-lapped to 5.2 mils, cleaned, and the n-side metallized. The wafer was scribed and cleaved every 25 mils instead of every 10 mils as with the "standard" device. The

wafers were de-mounted and the die cleaned thoroughly in organic solvents and dried in a dry nitrogen atmosphere.

VI. ASSEMBLY

Assembly of Single Element Lasers

Two package types were used for the assembly of the single element lasers.

- TO-46, 2 Lead Header with a wide, gold plated tungsten post
- TO-5 Copper stud package

In the first case, the dies were alloyed to the post and the second contact was obtained by wire bonding. Prior to the lens being fitted the devices were tested then organically cleaned followed by a 15 minute bake out in a dry nitrogen atmosphere at 100°C.

In the second case, the dies were attached to a BeO block whose dimensions were approximately 0.115 x 0.090 x 0.060 inches. This block had gold metallized pads to facilitate connections to the die. The die-block assembly was mounted in the TO-5 copper stud package and tested as above prior to the lens being fitted.

It was found, during assembly, that the planar device geometry was much easier to handle, ie., die attach and wire bonding could be performed with greater speed and accuracy and were less susceptible to damage due to assembly operations and handling.

Assembly of 20mw Average Power Laser Arrays

The unit consisted of 1 die per BeO block and 16 BeO blocks

arranged in four groups of four blocks per TO-5 copper stud header. A segmented ring surrounded the four BeO blocks to allow reduction in wire bond length. Triple bonds were used to minimize bond failure and increase current handling capabilities. The final configuration of the 16 BeO blocks was such that the area of the total emitting surface of the array was contained within a radius of 25 mils. Figure 5 shows the array configuration prior to the lens being fitted.

VII. TEST - SINGLE ELEMENT LASERS

Voltage Current Characteristics

The single element devices were checked for V-I characteristics at low current (typical plot shown in Figure 6). These tests were performed on a Tektronix 575 transistor curve tracer using 0.2v/division and 5ma/division scales. The 1.2V crossover of this test is such that certain device deficiencies are exposed. Some examples are as follows:

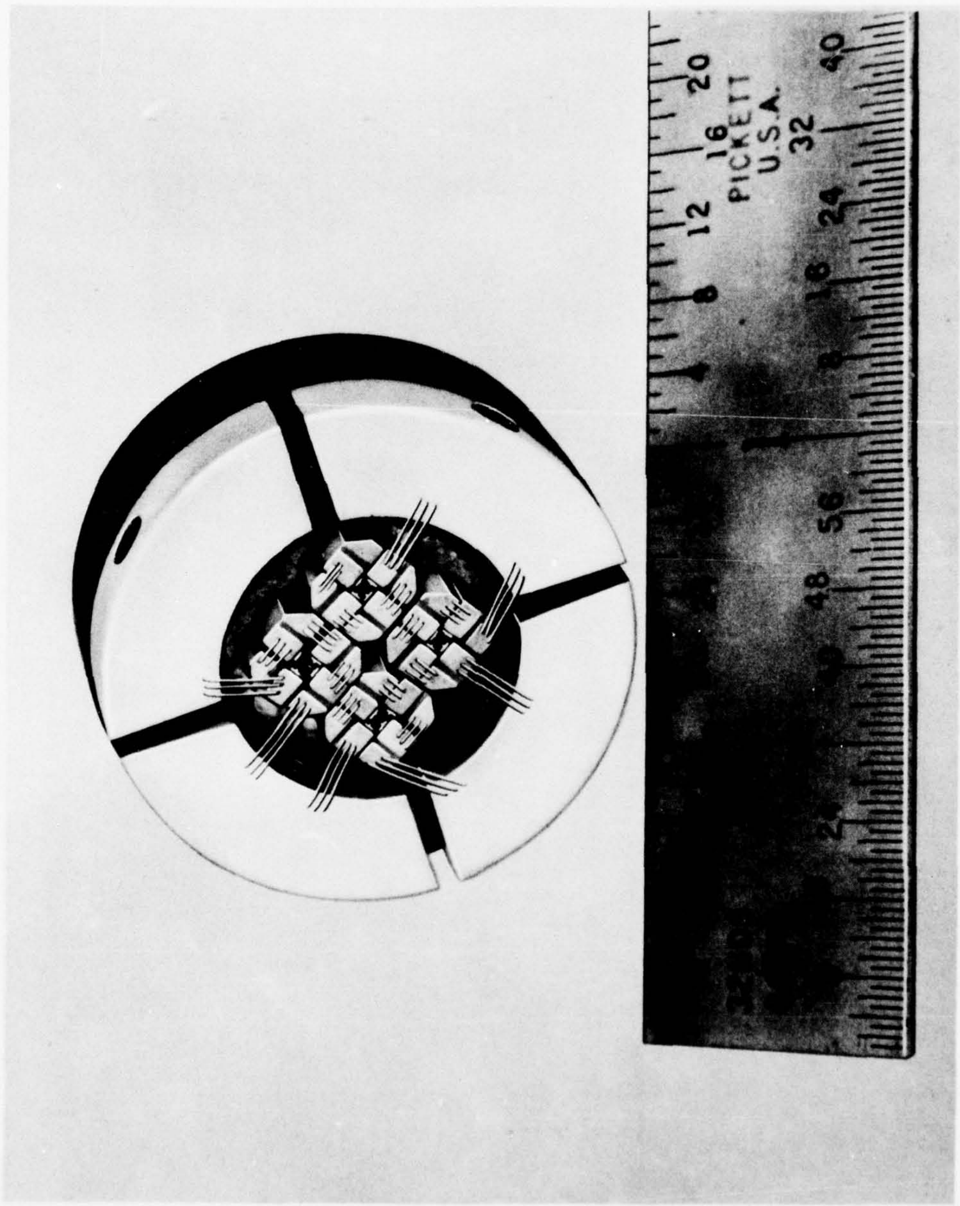
- Resistive Wire Bonds
- Bad Die Attaching Leading to Shorted Junctions, etc.
- Improper Doping

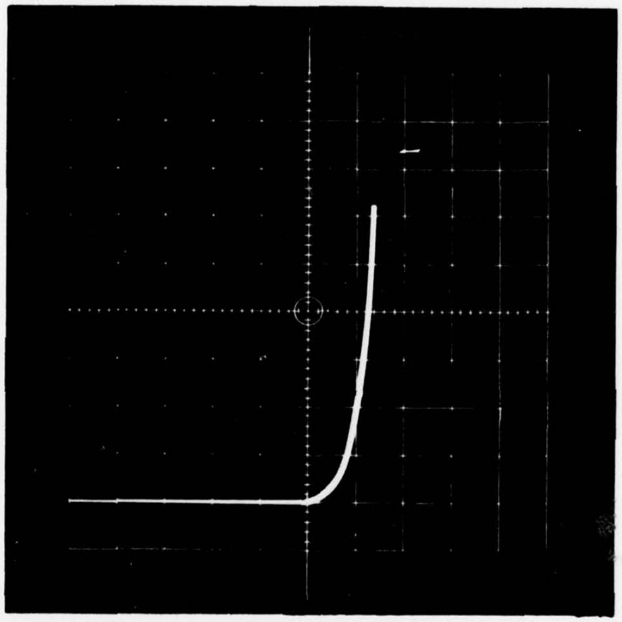
Peak Power vs. Peak Current Characteristics

The test set up used for these measurements is shown in Figure 7. The power source used in the series of tests was a Velonix 380 high power pulse generator having an output impedance of 0.50 ohm. Inter connection between the pulse generator and the test fixture was via a 0.50 ohm strip line which contained a group of paralleled precision resistors for line termination and current monitoring. An EG & G 444 detector was used to measure the laser

FIGURE 5

SIXTEEN ELEMENT 20mW AVERAGE POWER LASER
ARRAY PRIOR TO THE LENS BEING FITTED





Typical GaAsP Single Element Laser,
Low Current V-I Trace
Figure 6.

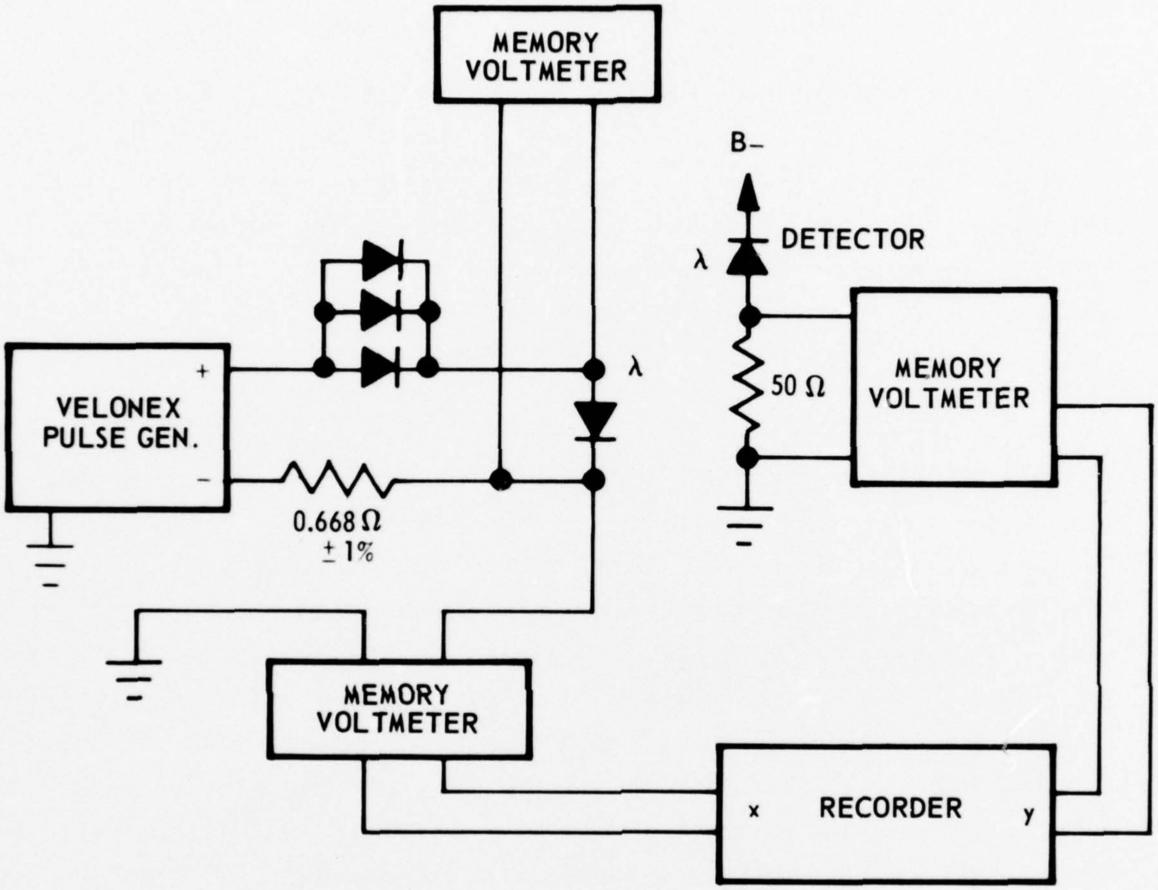


Figure 7. Peak Power vs Peak Current Characteristics Test Setup.

output. All measurements were performed with the detector as close to the laser as possible.

Output from the current monitoring resistors fed a memory voltmeter while output from the detector, terminated by 50 ohms, fed another memory voltmeter. Outputs from these memory voltmeters fed an X-Y recorder. Voltage across the laser diode was measured by a third memory voltmeter.

VIII. TEST RESULTS

"Standard" Single Element Laser

"Standard" single element laser test (Figure 8) results show that the "standard" laser mounted on a tungsten post package is somewhat inferior in operating duty cycle to the BeO package mounted on a TO-5 copper stud (Figure 9). Average powers were considerably higher with the better heat sink indicating that external efficiencies were higher for a given repetition rate. The maximum external power efficiency of devices measured at 100 ns and 1 KHz was 1.6 percent. After lensing it was found that absorption and diffusion in the lens caused a 5-20% drop in output power depending on the optical quality of the window.

Single Element "Planar" Laser

A typical planar device was capable of operating up to 50 KHz with a 100 ns pulse width and up to 100 KHz with a 50 ns pulse width. These devices had maximum external efficiencies of 2.1 percent. The typical average output power was 5 mw with devices capable of up to 10 mw. Figure 10 shows the peak power vs. peak current characteristics for devices mounted on tungsten post packages while Figure 11 shows the results obtained on BeO mounted dies in the TO-5 package.

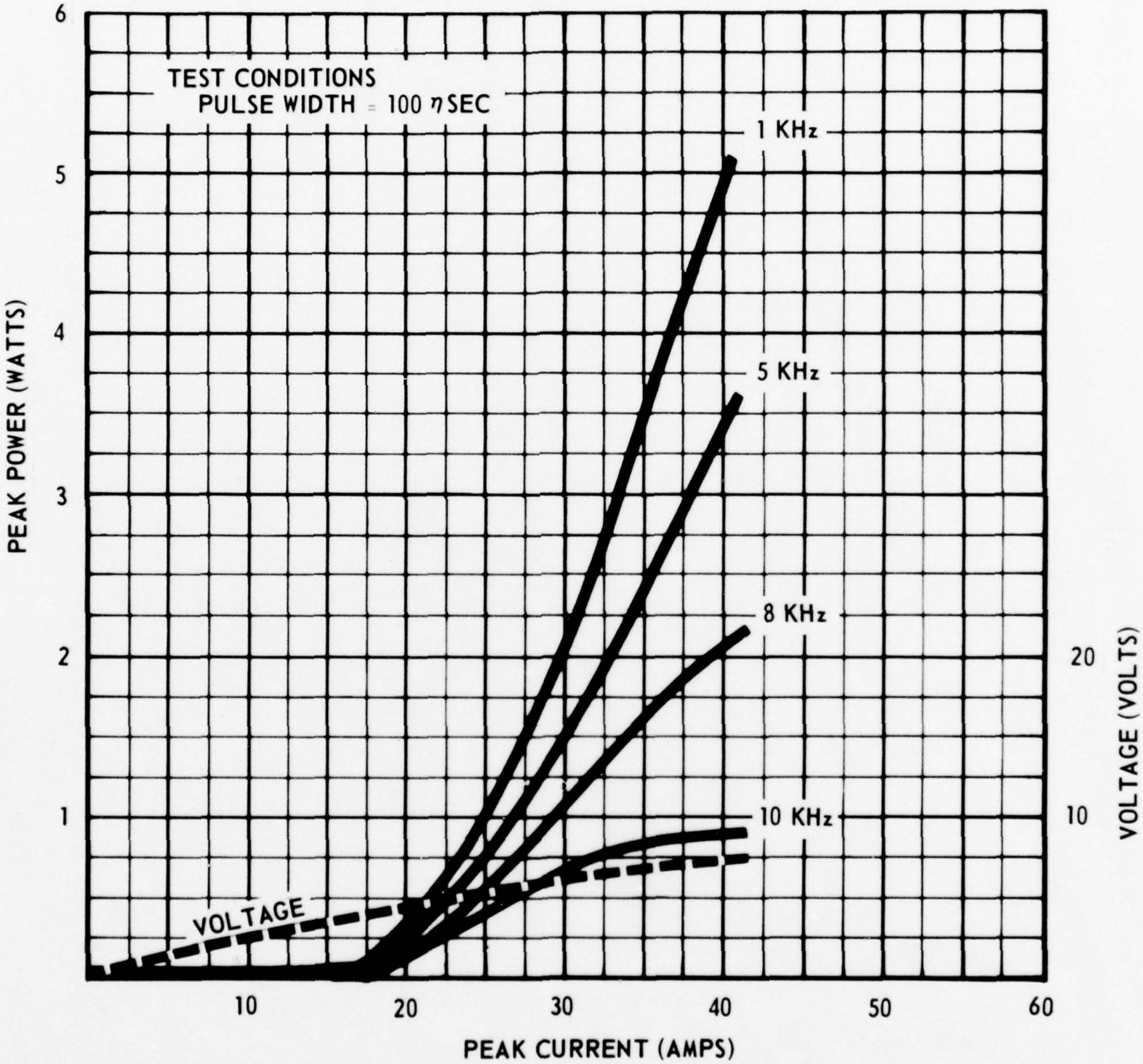


Figure 8 Typical Characteristics at Various Repetition Rates of Standard Device on Tungsten Post

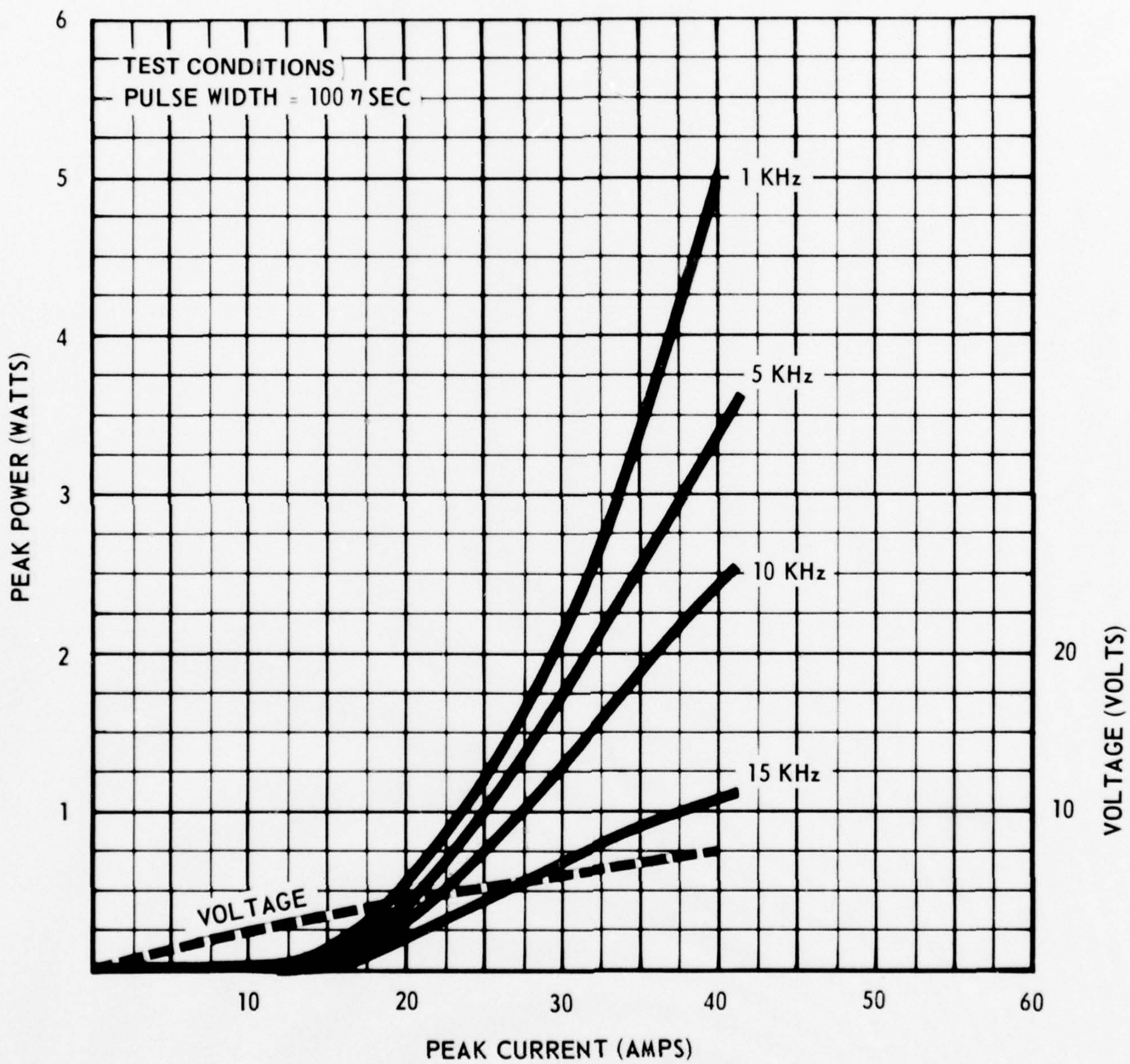


Figure 9 Typical Characteristics at Various Repetition Rates of Standard Device on BeO, Mounted on TO-5 Header

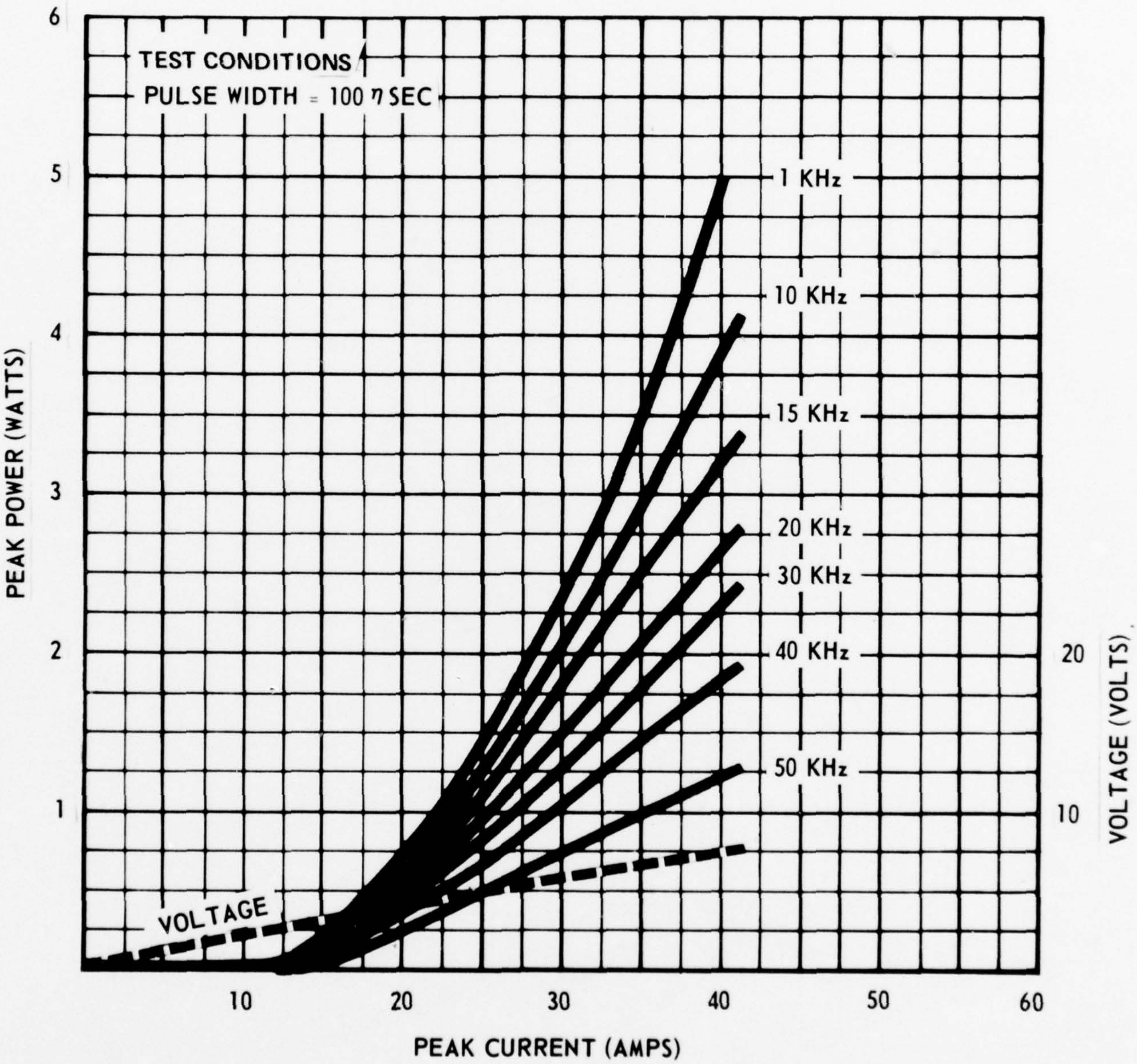


Figure 10 Typical Characteristics at Various Repetition Rates of Planar Device on Tungsten Post

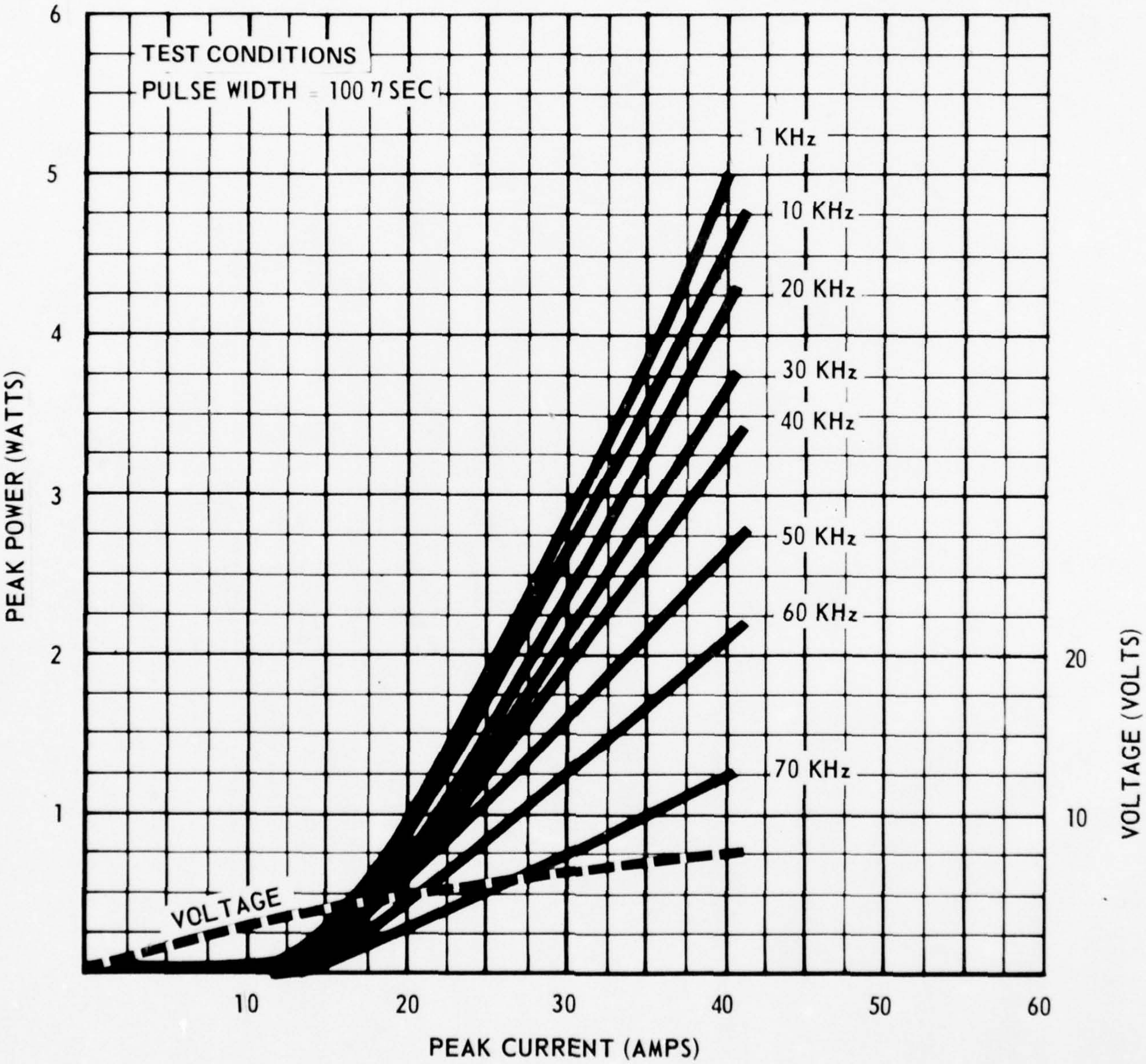


Figure 11 Typical Characteristics at Various Repetition Rates of Planar Device on BeO, Mounted on TO-5 Header.

Four Element Array

This device, at room temperature, was capable of 20 mw average power, using an 80ns pulse width at 30 KHz and a current of 44 amps (Figure 12). At 50 amps and 30 KHz the device was capable of 24 mw average power with no sign of heating such as bending over a peak output power curve. By comparison, the "standard" chip 4 element, made from the same wafer, was capable of an absolute maximum of 10mw with heating taking place.

Sixteen Element Array

The device achieved 20mw average power at 100ns, 4 KHz and 38.5 amps. The device was tested up to 44 amps where it had a peak output of 67 watts and average power of 26.8 mw. Figure 13 shows peak power vs. peak current obtained on the sixteen element array.

Test Summary

Figures 9 thru 13 are typical graphs of results obtained on single elements, arrays of 4 elements and an array of 16 elements. For the sake of clarity, Table II has been prepared and gives comparative results obtained on single element lasers for the several configurations fabricated during the course of the program. Table III compares actual results vs. the specification requirements.

IX. CONCLUSIONS

During the course of fabrication and evaluation of the elemental devices and the array, it was apparent that the BeO block mounted planar device was superior to the other configurations fabricated.

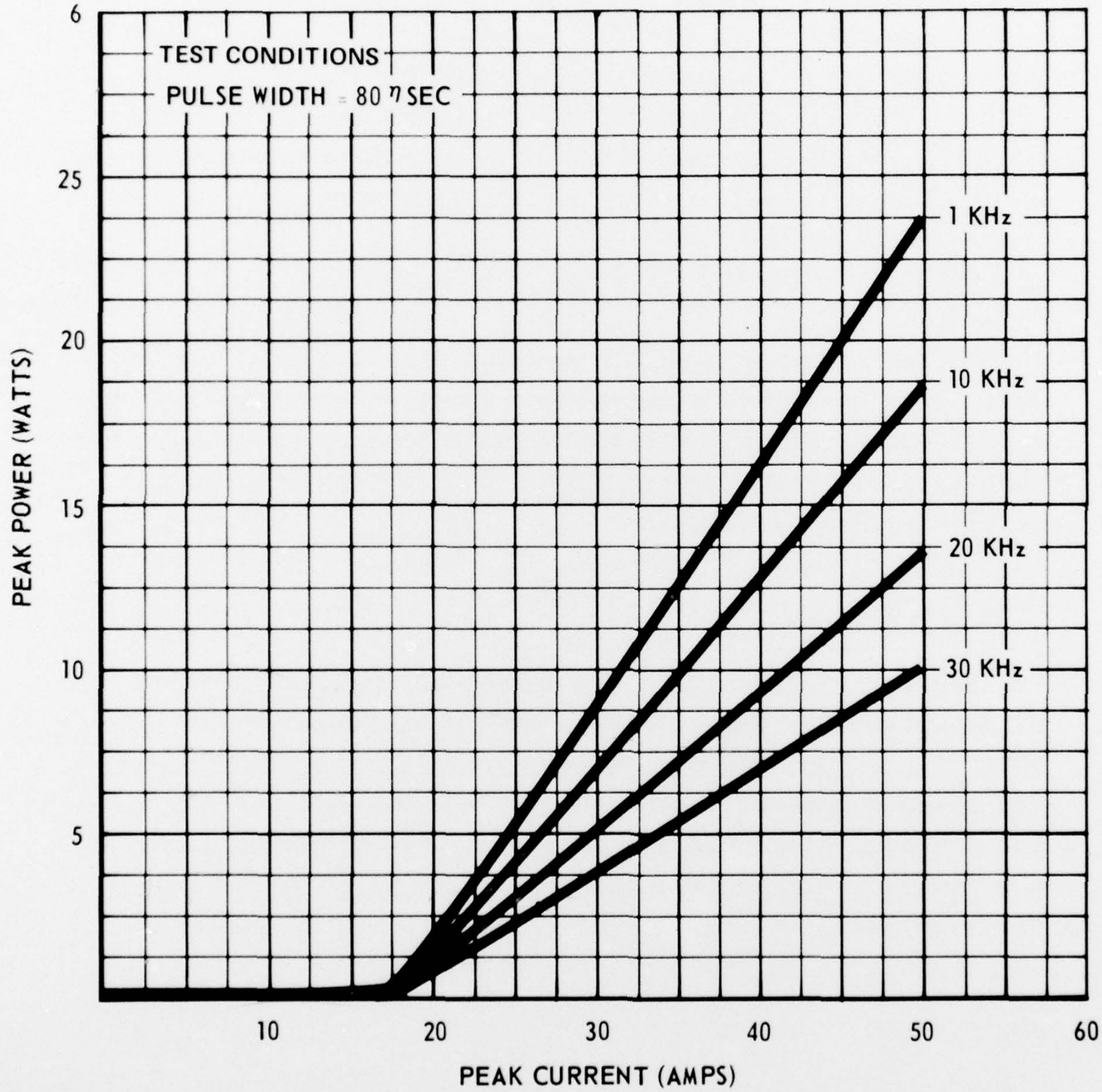


Figure 12. Four Element Planar Array Peak Power vs Peak Current Characteristics at Various Repetition Rates.

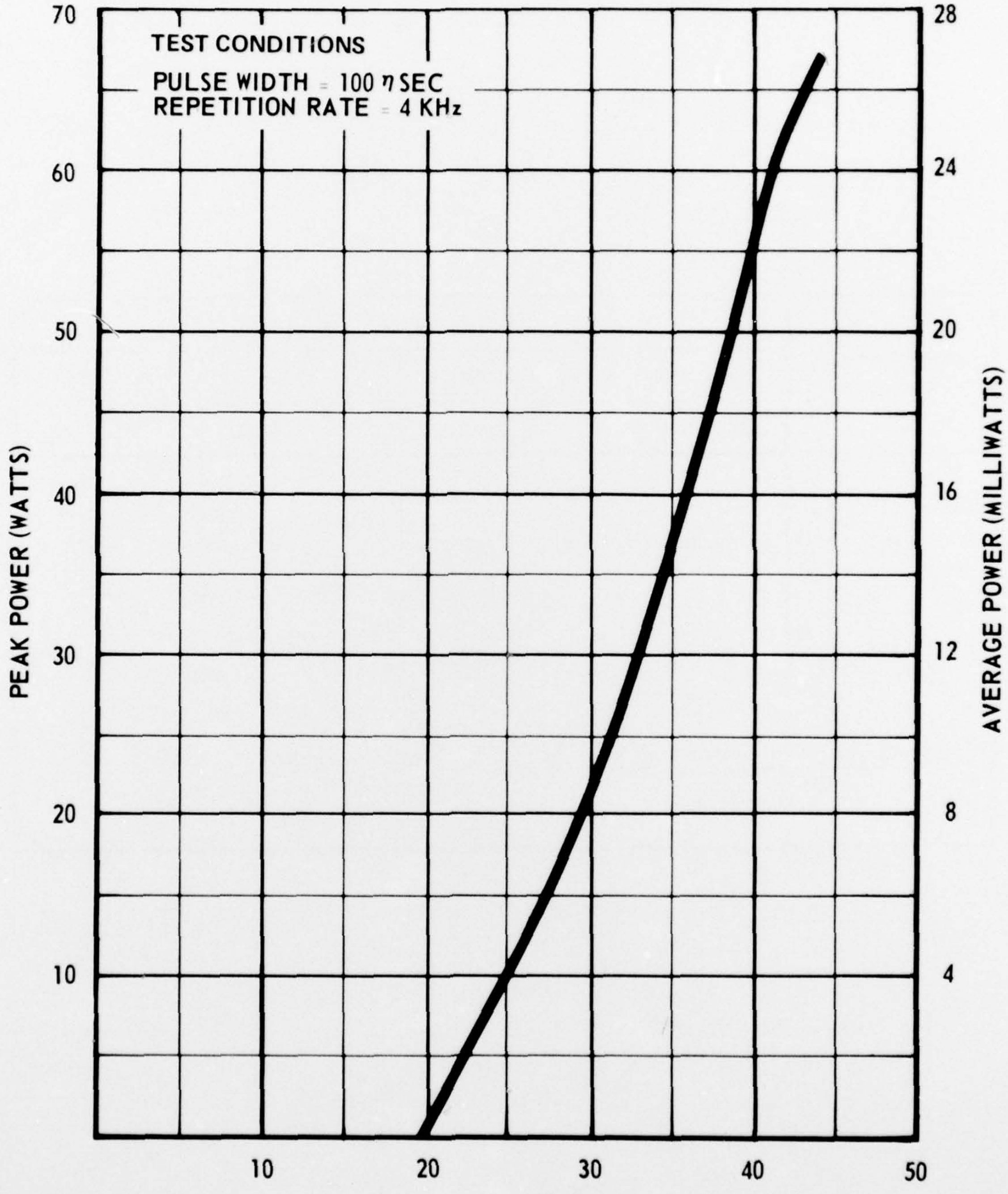


Figure 13. Sixteen Element Planar Array. Peak Power vs Peak Current Characteristics.

TABLE II

COMPARISON OF RESULTS OBTAINED ON SINGLE ELEMENT LASERS

Peak Power Vs. Repetition Rate at a Peak Current of 35A and Pulse Width of 100 ns

Repetition Rate	PEAK POWER (WATTS)			
	Tungsten Post Package		BeO Block Mounted	
	Standard	Planar	Standard	Planar
1 KHz	3.40	3.40	3.30	3.75
10 KH_z	0.85	2.90	1.90	3.55
15 KH_z	Overheating and probable failure if tested.	2.50	0.90	3.40

TABLE III

COMPARISON OF TEST RESULTS AND SPECIFICATIONS

	Specification	Actual
Wavelength	8575Å $^{+150}_{-50}$ Å	8560 Å
Average Power per device at room temperature	1 mW	1.4 mW
External efficiency per device	1.0%	1.0% to 2.09%
Sixteen element array average power	20 mW	22.5 mW

The evidence for this is as follows:

- Mechanical

  The larger chip size, five times wider, is easier to handle for die attach operations and provides a larger surface for wire bonding. The net result is a higher yield of good devices.

- Thermal

  Higher average power output was obtained from the BeO mounted planar devices.

- Efficiency

  Planar devices were slightly more efficient than the standard devices.

- Power Output

  Three to five times the average power output was obtained from the planar devices compared to that obtained from the standard devices. For the planar device, up to a maximum recommended 3 times threshold current, the power output vs. current input curve remained relatively linear indicating freedom from junction overheating.

- Lifetime

  Preliminary data, given in Appendix I, indicates that the standard device has approximately 70% of the original power output available after 600 hours operation whereas the planar device shows approximately 80% at 1000 hours and 54% at 2100 hours.

X. RECOMMENDATIONS

During the course of the program, GaAsP laser diodes were delivered meeting the requirements of the specifications. In order, however, to improve these devices it is suggested that the following areas be investigated more thoroughly.

Materials

- More precise process control to give tighter center wavelength (± 20Å) without reducing yield.

Devices

- Reflective coating one end of the device to increase output from the opposite face.
- Further lower the package thermal impedance in conjunction with 'P' side down bonding.

Reliability

- Environmental limitations of device.
- Factors that contribute to device degradation.

APPENDIX I

PRELIMINARY LIFETIME DATA ON GaAsP LASER DIODES

LIFETIME

This data, obtained on a limited number of samples, is significant, and therefore, is included as a part of this report for completeness.

The data presented in Figures 14 and 15 was obtained on "standard" devices BeO block mounted on a TO-5 header. Figure 14 shows high, low and average results for 3 of these diodes while Figure 15 shows the same for 5 other diodes.

The data presented in Figure 16 was obtained on 2 planar devices BeO block mounted in TO-5 headers and is the average value obtained.

From the data presented in Figures 14 thru 16, it can be seen that after approximately 500 hours operation, 70% of the original power output is available from the standard device, whereas, under similar conditions, the 70% point for planar devices is not reached until approximately 1030 hours of operation.

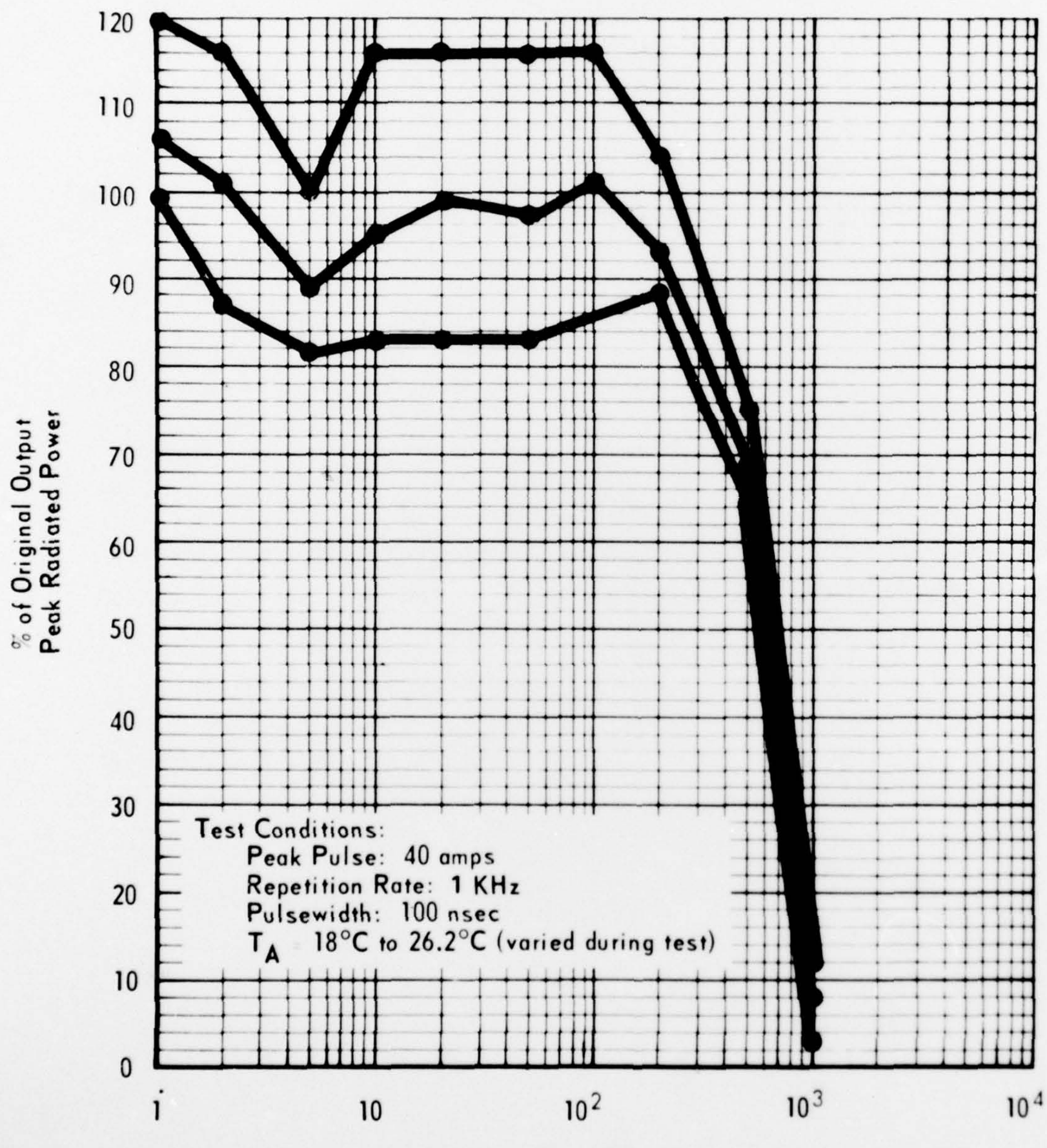


Figure 14. Life Test Data for 3 Standard Devices; BeO Block Mounted on TO-5 Header

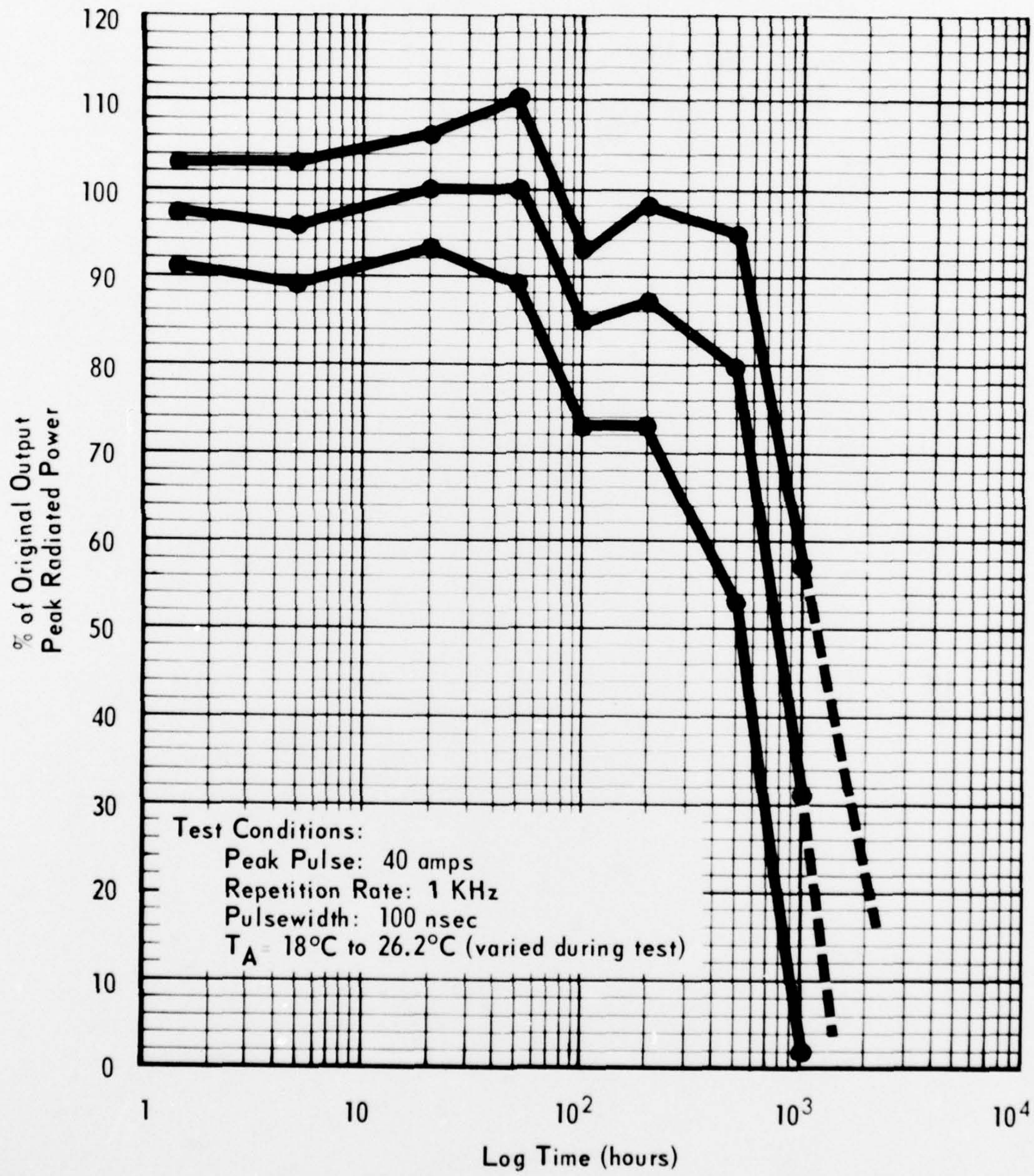


Figure 15. Life Test Data for 5 Standard Devices; BeO Block Mounted on TO-5 Header

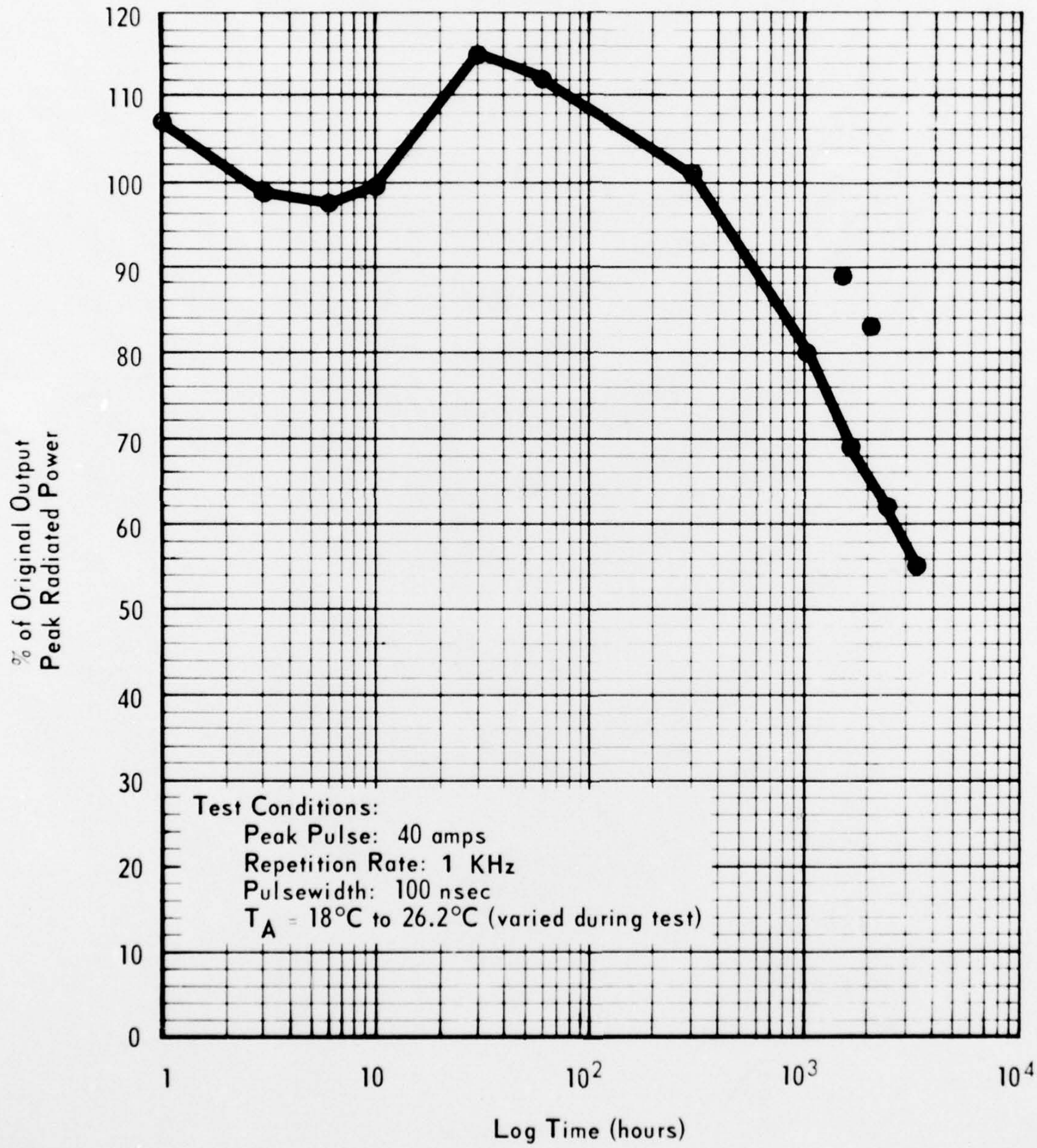


Figure 16. Life Test Data for 2 Planar Devices; BeO Block Mounted on TO-5 Header

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11. SUPPLEMENTARY NOTES ----------------	12. SPONSORING MILITARY ACTIVITY U.S. Army Engineering R & D Lab. Fort Belvoir, Virginia

13. ABSTRACT

Fabrication and test of single element lasers demonstrated that devices built using planar techniques were superior to rectangular parallelepiped devices and, at room temperature, gave 5 watts peak power output for a current input of 40 amps peak, having a duration of 100 nanoseconds at a repetition rate of 1KHz. Higher repetition rates for the planar device gave less degradation in performance than that obtained from the rectangular parallelepiped geometry.

Using the planar devices a sixteen element array was constructed whose emitting area was within the confines of a TO-5 header. 55 watts peak power output was demonstrated on this device for a current pulse of 40 amps peak power having a duration of 100 nanoseconds at a repetition rate of 4 KHz. The array average power output was then 22 mw. (U)

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UNCLASSIFIED

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Room Temperature Solid State Laser						
Rectangular Parallelepiped Laser						
Planar Laser						
Multi-Element Laser Arrays						